DELAY EFFICIENT MAC PROTOCOL FOR DIFFUSION BASED ROUTING IN WIRELESS SENSOR NETWORKS

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Abstract: In this paper we present DESMAC a contention based Medium Access Control protocol for Diffusion based routing in Wireless Sensor Networks. One of the main challenges in WSNs is to balance delay efficiency and energy consumption. Surveillance and monitoring application as well as many other need low latency data delivery; but, since sensor nodes have a small source of energy usually Active/Sleep cycles are used to reduce the energy consumption which causes higher delay. We use routing information to adaptively change the duty cycle for different loads. In our Cross Layer Design the Routing Layer can manipulate the duty cycle of underlying MAC protocol. The diffusion control messages are used to adapt the duty cycle to variation in the load. Also extensive use of some nodes can damage the connectivity of network. Therefore we provide a mechanism to balance the load between several possible paths. We discuss DESMAC design and compare our simulation results to S-MAC and IEEE 802.11 standard. DESMAC achieves significant latency reduction (up to 50 times better delay than S-MAC) while ensuring energy efficiency and load balanced delivery.

1 INTRODUCTION

The goal of a wireless sensor network is reliable data reporting and minimum energy consumption. Sensor nodes have a small supply of energy which makes power management a great criterion in protocol design for this kind of networks. Motes can last approximately around 100-120 hours on a pair of AA batteries in active mode (Kumar et al., 2006) and battery capabilities only double every 35 years.

Several methods have been proposed to put sensor nodes to inactive mode when the application of the sensor network is able to tolerate the effects (Ye, Heidemann and Estrin, 2004) (van Dam and Langendoen, 2003) Putting nodes to inactive mode reduces the idle listening time which is one of the major sources of energy wastage. On the other hand it causes higher delay, lower coverage & lower connectivity in exchange for energy efficiency. Since many applications have delay or coverage criterion, use of many sleep scheduling schemes can be limited (Akyildiz et al., 2002).

Medium Access Control protocols in wireless sensor networks need to be energy efficient since it is usually impossible to replace or recharge the batteries. Moreover many applications have latency and data rate requirements. Balancing the trade-off between energy efficiency and delay efficiency has been subject of great deal of research. Adaptive adjustment of MAC layer's duty cycle based on current load and application needs is one of the possible solutions. MAC layer's information about the network is usually not sufficient and vague for example MAC layer usually does not have the information necessary to determine if degradation of data transmission is due to a neighbor's failure or a temporary distortion, etc. One of the ways to meet both the energy and delay criterion of applications is by using the help of Routing and Application layer information to optimize the duty cycle of the MAC layer based on the current load and situation.

Diffusion based routing algorithms are very popular in wireless sensor networks (Intanagonwiwat et al., 2003), (Ganesan, et al., 2001). Routes are created on demand when an event occurs and are not maintained by all sensors all the time. All nodes in diffusion based routing are application-aware. Directed Diffusion's messages can be used for adjustment of MAC layer's duty cycle to provide delay efficient data transfer.

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2 DESMAC

We introduce a novel cross layer design to reduce latency caused by periodic sleeping of the nodes. Routing and application are used to help the MAC protocol better adjust itself. We use S-MAC as the basic framework for our design and adaptively change its duty cycle. We assume that the reader is familiar with S-MAC and Directed Diffusion (for further reading please refer to (Ye, Heidemann and Estrin, 2004) and (Intanagonwiwat et al., 2003)).

In this approach we use routing layer control messages to adaptively reduce the sleep period of the MAC layer of the nodes that take part in the routing process. We decrease the sleep period of the nodes that are reinforced by Directed Diffusion for routing purposes. Nodes that are not reinforced preserve their current sleep schedule.

In Directed Diffusion sink periodically sends interest messages to all nodes in the network. When a node detects an event which matches the diffused interests it becomes a data source and starts sending exploratory data messages. These messages are forwarded towards the sink. When the sink receives a positive reinforcement it issues a *positive reinforcement*.

Positive reinforcements are similar to interest messages but have lower interval. Each node compares this interest message with the fields in its own cache and if a lower interval is detected, it updates its gradient toward that node to the new value. In our approach positive reinforcements also trigger a sleep period reduction in the MAC layer.

Negative Reinforcements have the exact opposite effect on the sleep period. Negative reinforcements in Directed Diffusion are used to reduce the number of reinforced paths and path repairs. Several mechanisms for negative reinforcement are introduced in directed diffusion (timeouts, gradient reductions, etc). Any mechanism for negative reinforcement used by Directed Diffusion also triggers an increase in the sleep period of the MAC layer.

The goal is to benefit from energy saving features of S-MAC and have much lower latency in comparison to it. Nodes that are not reinforced by the Directed Diffusion have the same duty cycle as S-MAC, But nodes that are reinforced increase their active period exponentially therefore upon path establishment nodes on the path are almost always active which results in very low latency that is comparable to IEEE802.11.

Nodes that are not part of routing preserve their original duty cycle and have similar energy consumption to S-MAC. But routing nodes have high duty cycle which provide very low latency and can meet the application criteria.

In case a path failure or degradation occurs, the path is negatively reinforced by Directed Diffusion which will reduce the duty cycle of the nodes previously involved in the routing. Therefore nodes that are no longer involved in routing have low duty cycle and energy saving is maximized.

S-MAC works on the basis that neighbor nodes wake up at the same time therefore they can hear each other's broadcast messages (SYNC, RTS/CTS). If neighbor nodes don't have synchronous schedules, communication between them becomes impossible.

Dynamic reduction of sleep period can disrupt the synchronization done in the SYNC period of S-MAC.

To address this problem we reduce the sleep period in a manner that the SYNC and listen period of the new schedule is still synchronized with that of neighbor nodes. In order to achieve synchronized wakeups we increase the duty cycle exponentially. The sleep period in S-MAC is much longer than the listen period therefore it is possible to reduce it so that the frame size is divided in half. Each frame turns into two frames with SYNC, RTS/CTS, and sleep period which means that each positive reinforcement message doubles the duty cycle of the node until it achieves maximum possible duty cycle This is shown in Figure 1.

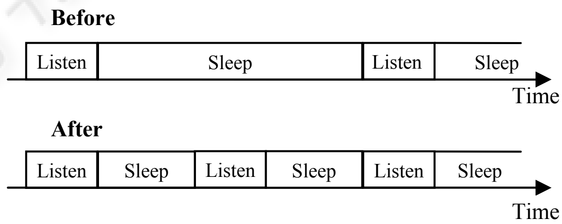

Figure 1: Change in Duty Cycle as a node receives a reinforcement message. Beginning of Listen periods is still synchronized.

Increasing the duty cycle in this fashion does not disrupt the synchronized wakeup of the neighbor nodes. Nodes that are on the same path have the same duty cycle. These nodes wakeup more often and have more time for transmitting data therefore provide lower latency and higher throughput. These nodes are still able to communicate with the nodes that have different duty cycles. Since the duty cycle is increased exponentially the neighbor nodes still have the synchronized wakeup. Nodes active in the routing process have very small sleep periods and show similar behavior to 802.11. But nodes not involved behave similar to S-MAC.

3 LOAD BALANCING

Nodes that are involved in routing for a long period will fail faster since they have higher energy consumption as a result of higher duty cycle. Failure of these nodes can cause the network to be partitioned and other unwanted side effects such as reduced coverage and connectivity.

In dense sensor networks, multiple paths may exist between a source and destination; therefore, it is desirable to use all these paths to efficiently use the energy in a distributed manner. (Ganesan, et al., 2001) is an example of a diffusion based multipath routing algorithm. Directed Diffusion's nature makes it a good candidate for multipath routing since initially reinforces several paths and then tries to reduce the number of paths by using negative reinforcements. In our cross layer design we use this multipath potential of Directed Diffusion to adjust MAC layer's duty cycle to balance the network load based on remaining routing nodes' energy. We define a critical remaining energy limit for the nodes. When a node hits this critical limits it will dramatically reduce its duty cycle which will degrade the data delivery rate to the sink node. This degradation is detected by Directed Diffusion and triggers the local path repair mechanism. In local repair mechanism a chain of local interactions result in another path establishment that does not contain the node that has reached the critical energy limit. In a dense network where there are several neighbor nodes that can replace a node with low energy level this mechanism can be used to efficiently distribute energy consumption on neighboring nodes.

In order to provide more control over different energy levels we define several duty cycle reduction levels. When a node reaches the predetermined critical energy level it reduces its duty cycle to half the original duty cycle in the deployment time. To maintain the synchronization between sensor nodes duty cycle reduction is exponential (similar to path reinforcements). Every time a node reaches a new energy level it will trigger a duty cycle reduction in the same manner. For example if three energy levels are defined the duty will be reduced up to one eight of the original duty cycle. The critical energy limit and different energy levels can be defined based on the network, traffic, and application characteristics. These levels can also be dynamically changed based on current network situation and application needs.

4 SIMULATIONS

We compare our MAC protocol to 802.11 and S-MAC. We used NS-2 for our simulations. Latency and energy consumption of a Directed Diffusion application on three MAC protocols: 802.11, S-MAC, Delay Efficient S-MAC (DESMAC) will be compared. The initial energy of the nodes is 3000 joules. To compare the energy consumption of each protocol we use the power consumption model of Cabletron 802.11 network interface card in Transmit, Receive, Idle, and Sleeping modes (Chen, et al., 2002). Nodes' deployment is grid and source and sink are at the ends of grid's diagonal. Some simulation results are not included due to space limitations.

Figure 2 compares the latency between S-MAC and DESMAC and IEEE802.11. As shown average delay in DESMAC is much lower than S-MAC. Since S-MAC is not able to transfer data message with the required rate, queuing delay makes the behavior of S-MAC unpredictable. It can also trigger unwanted path changes in Directed Diffusion since it may falsely detect degradation in the current path because of high jitter. DESMAC on the other hand shows a much more stable behavior. Small path changes because of load balancing mechanism create a small variation in DESMAC's delay. As expected delay of IEEE802.11 is lower than DESMAC (always near zero).

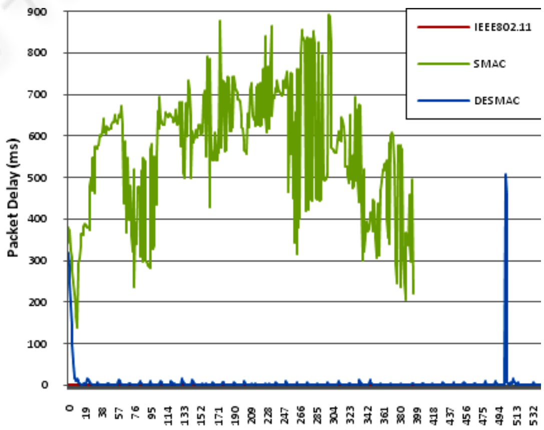

Figure 2: Comparison of Packet delivery delay in different MAC protocols for 6×2 grid deployment.

Figure 3 compares the energy consumption of S-MAC, DESMAC, and IEEE802.11. IEEE802.11 has the highest energy consumption since nodes are always active and nodes fail much sooner than other protocols (mid-way during simulation). DESMAC has higher energy consumption than S-MAC because nodes involved in routing have higher energy consumption than nodes with the normal duty cycle.

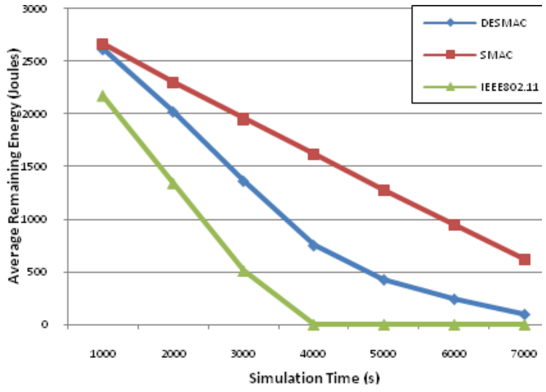

Figure 3: Comparison of energy consumption in different MAC protocols.

Figure 4 compares the average remaining energy of the network.

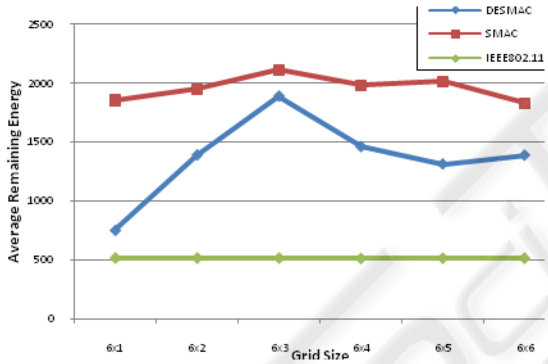

Figure 4: Average network remaining energy for different network sizes.

IEEE 802.11 as expected has the highest energy consumption. Nodes are always active and the number of nodes involved in routing doesn't affect the average total remaining energy of the network. S-MAC has the lowest energy consumption, and similar to IEEE 802.11 average remaining energy doesn't depend on the number of involved nodes in routing. DESMAC's total remaining energy is somewhat close to S-MAC but since nodes involved in routing have higher energy consumption total remaining energy decreases as the number of these nodes grow. The network size has another effect on the average remaining energy. As number of paths increases multiple path changes becomes possible and different nodes during simulation may become involved in routing therefore number of nodes that have very high duty cycle decreases. This results in lower energy consumption in network. But as network size grows further number of nodes involved in routing becomes a high percentage of the deployed nodes therefore total remaining energy of the network decreases.

5 CONCLUSIONS

In this paper we presented DESMAC, a delay efficient MAC protocol for diffusion based routing in wireless sensor networks. It supports power saving features and adapts to data transmission load in different situations. DESMAC does not pose any messaging overhead for its adaptive duty cycling (Since the control messages of Directed Diffusion are used) and load balancing. It has much lower delay in data transmission in comparison to S-MAC and has much better energy consumption in comparison to IEEE 802.11. In order to avoid failure of nodes involved in routing due to higher energy consumption in these nodes DESMAC changes the path when these nodes hit a critical energy limit. This results in higher network longevity and preserving of network connectivity.

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